

**The  $D^0\bar{D}^0$  Mixing Search — Current Status and Future Prospects \***

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The search for  $D^0\bar{D}^0$  mixing carries a large discovery potential for new physics since the  $D^0\bar{D}^0$  mixing rate is expected to be very small in the Standard Model. The past decade has seen significant experimental progress in sensitivity, from 20% down to 0.37%. This paper discusses the techniques, current experimental status, and future prospects for the mixing search. Some new ideas, applicable to future mixing searches, are introduced. The conclusion is that while it is possible that the mixing sensitivity may decrease to  $10^{-5}$  around the year 2000, reaching the  $10^{-6}$  level will certainly be quite difficult.

**1 Introduction**

Following the discovery of the  $D^0$  meson at SPEAR in 1976, experimenters began to search for  $D^0\bar{D}^0$  mixing, using a variety of techniques. The past decade has seen significant experimental progress in sensitivity (from 20% to 0.37% [1] to [13]), as can be seen in Figure 1. Much of the enthusiasm for searching for  $D^0\bar{D}^0$  mixing stems from the belief that the search carries a large discovery potential for New Physics, since the mixing rate  $R_{\text{mixing}} \equiv \mathcal{B}(D^0 \rightarrow \bar{D}^0 \rightarrow \bar{f}) / \mathcal{B}(D^0 \rightarrow f)$  is expected to be very small in the Standard Model. One can characterize  $D^0\bar{D}^0$  mixing in terms of two dimensionless variables:  $x = \delta m / \gamma_+$  and  $y = \gamma_- / \gamma_+$ , where the quantities  $\gamma_{\pm}$  and  $\delta m$  are defined by  $\gamma_{\pm} = (\gamma_1 \pm \gamma_2)/2$  and  $\delta m = m_2 - m_1$  with  $m_i, \gamma_i$  ( $i = 1, 2$ ) being the masses and decay rates of the two CP (even and odd) eigenstates. Assuming a small mixing, namely,  $\delta m, \gamma_- \ll \gamma_+$  or  $x, y \ll 1$ , we have  $R_{\text{mixing}} = (x^2 + y^2)/2$ . Mixing can be caused either by  $x \neq 0$  (meaning that mixing is genuinely caused by the  $D^0 - \bar{D}^0$  transition) or by  $y \neq 0$  (meaning mixing is caused by the fact that the fast decaying component quickly disappears, leaving the slow decaying component which is a mixture of  $D^0$  and  $\bar{D}^0$ ). Theoretical calculations of  $D^0\bar{D}^0$  mixing in the Standard Model are plagued by large uncertainties. While short distance effects from box diagrams are known [14] to give a negligible contribution ( $\sim 10^{-10}$ ), the long distance effects from second-order weak interactions with mesonic intermediate states may give a much larger contribution. Estimates of  $R_{\text{mixing}}$  from long distance effects range from  $10^{-7}$  to  $10^{-3}$  [15]. However, it has recently been argued by Georgi and others that the long distance contributions are smaller than previously estimated, implying that cancellations occur between contributions from different classes of intermediate mesonic states [16], and the prevailing conclusion within the Standard Model seems to be that  $R_{\text{mixing}} < 10^{-7}$  [17]. A measurement of such a small mixing rate is not possible with present experimental sensitivity. However, the observation of a larger value for  $R_{\text{mixing}}$  caused by  $x \neq 0$  would imply the existence of new physics beyond the Standard Model [18]. Examples includes flavor-changing neutral currents mediated by the exchange of a non-standard Higgs scalar with a mass of a few TeV/ $c^2$ , which could lead to  $R_{\text{mixing}}$  as large as 0.5%.

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Recently, CLEO has observed a signal for  $D^0 \rightarrow K^+\pi^-$  [19], and found  $R = \mathcal{B}(D^0 \rightarrow K^+\pi^-) / \mathcal{B}(D^0 \rightarrow K^-\pi^+) \sim 0.8\%$  [20]. Normally,  $D^0$  decays by Cabibbo favored decay  $D^0 \rightarrow K^-\pi^+$  and  $\bar{D}^0 \rightarrow K^+\pi^-$ . A signal for  $D^0 \rightarrow K^+\pi^-$  could indicate mixing of  $D^0 \rightarrow \bar{D}^0$ . But it could also indicate a different decay channel, namely, Doubly Cabibbo Suppressed Decay (DCSD)  $D^0 \rightarrow K^+\pi^-$ , which is suppressed with respect to the Cabibbo favored decay by a factor of  $\tan^4\theta_C \sim 0.3\%$  where  $\theta_C$  is the Cabibbo angle. Unfortunately, without a precision vertex detector, CLEO is unable to distinguish a potential mixing signal from DCSD. As Purohit pointed out [21]: “The CLEO II result makes the entire subject of  $D^0\bar{D}^0$  mixing very interesting. It really calls for a fixed-target experiment to use its decay time resolution to decide whether the signal is due to DCSD or mixing”. If the number of reconstructed charm decays can reach  $10^8$  around the year 2000, that would allow one to reach a new threshold of sensitivity to  $D^0\bar{D}^0$  mixing, and perhaps actually observe it. This is why charm mixing has been singled out for its own working group at this workshop.

This paper is organized as follows: Section 2 discusses the techniques which can be used to search for mixing, including two new ideas. One of them is to use  $D^0 \rightarrow K^+K^-, \pi^+\pi^-$  etc. to study mixing (see 2.1.1), and the other is to use the difference in the resonant substructure in  $D^0 \rightarrow K^+\pi^-\pi^0, D^0 \rightarrow K^+\pi^-\pi^+\pi^-$  etc. to distinguish mixing and DCSD (see 2.1.2). In each case, the relevant phenomenology will be briefly presented. Section 3 discusses the present status and future prospects of searching for mixing at different experiments. In section 4, a comparison of the future prospects of the different experiments with different techniques will be given. A brief summary is in Section 5.

## 2 The Techniques

The techniques which can be used to search for mixing can be roughly divided into two classes: hadronic and semi-leptonic. Each method has advantages and limitations, which are described below.

### 2.1 Hadronic method

The hadronic method is to search for the  $D^0$  decays  $D^0 \rightarrow K^+\pi^-(X)$ . These decays can occur either through  $D^0\bar{D}^0$  mixing followed by Cabibbo favored decay  $D^0 \rightarrow \bar{D}^0 \rightarrow K^+\pi^-(X)$ , or through DCSD  $D^0 \rightarrow K^+\pi^-(X)$ . This means that the major complication for this method is the need to distinguish between DCSD and mixing [22]. The hadronic method can therefore be classified according to how DCSD and mixing are distinguished. In principle, there are at least three different ways to distinguish between DCSD and mixing candidates experimentally: (A) use the difference in the decay time-dependence; (B) use the possible difference in the resonant substructure in  $D^0 \rightarrow K^+\pi^-\pi^0, K^+\pi^-\pi^+\pi^-$ , etc. modes; (C) use the quantum statistics of the production and the decay processes.

Method (A) requires that the  $D^0$  be highly boosted and so that the decay time information can be measured. Method (B) requires knowledge of the resonant substructure of the DCSD decays, which is unfortunately something about which we have no idea at this time. Finally, method (C) requires that one use  $e^+e^-$  annihilation in the charm threshold region. In the following, we will discuss these three methods in some detail.

#### 2.1.1 Method A –use the difference in the time-dependence of the decay

This method [23] is to measure the decay time of the  $D^0 \rightarrow K^+\pi^-$  decay. Here the  $D^0$  tagging is usually done by using the decay chain  $D^{*+} \rightarrow D^0\pi_s^+$  followed by  $D^0 \rightarrow K^+\pi^-$ . The  $\pi_s^+$  from  $D^{*+}$  has a soft momentum spectrum and is referred to as the slow pion. The idea is to search for the wrong sign  $D^{*+}$  decays, where the slow pion has the same charge as the kaon arising from the  $D^0$  decay. This technique utilizes the following facts: (1) DCSD and mixing have different decay time-dependence, which will be described below. (2) The charge of the slow pion is correlated with the charm quantum number of the  $D^0$  meson and thus can be used to tag whether a  $D^0$  or  $\bar{D}^0$  meson was produced in the decay  $D^{*+} \rightarrow D^0\pi_s^+$  or  $D^{*-} \rightarrow \bar{D}^0\pi_s^-$ . (3) The small  $Q$  value of the  $D^{*+}$  decay results in a very good mass resolution in the mass difference

$\Delta M \equiv M(D^{*+}) - M(D^0) - M(\pi_s^+)$  and allows a  $D^{*+}$  signal to be obtained with very low background. (4) The right sign signal  $D^{*+} \rightarrow D^0 \pi_s^+$  followed by  $D^0 \rightarrow K^-\pi^+$  can be used to provide a model-independent normalization for the mixing measurement.

A pure  $D^0$  state generated at  $t = 0$  decays to the  $K^+\pi^-$  state either by  $D^0\bar{D}^0$  mixing or by DCSD, and the two amplitudes may interfere. The amplitude for a  $D^0$  decays to  $K^+\pi^-$  relative to the amplitude for a  $D^0$  decays to  $K^-\pi^+$  is given by

$$A = \sqrt{R_{\text{mixing}}/2} t + \sqrt{R_{\text{DCSD}}} e^{i\phi} \quad (1)$$

where  $\phi$  is an unknown phase,  $t$  is measured in units of average  $D^0$  lifetime. Here  $R_{\text{DCSD}} = |\rho|^2$  where  $\rho$  is defined as  $\rho = \text{Amp}(D^0 \rightarrow K^+\pi^-)/\text{Amp}(\bar{D}^0 \rightarrow K^+\pi^-)$ , denoting the relative strength of DCSD. We have also assumed a small mixing; namely,  $\delta m, \gamma_- \ll \gamma_+$  or  $x, y \ll 1$ , and CP conservation.

The first term, which is proportional to  $t$ , is due to mixing and the second term is due to DCSD. It is this unique attribute of the decay time-dependence of mixing which can be used to distinguish between DCSD and mixing. Now we have:

$$I(D^0 \rightarrow K^+\pi^-)(t) \propto (R_{\text{DCSD}} + \sqrt{2R_{\text{mixing}}R_{\text{DCSD}}} t \cos\phi + 1/2 R_{\text{mixing}} t^2) e^{-t} \quad (2)$$

Define  $\alpha = R_{\text{mixing}}/R_{\text{DCSD}}$ , which describes the strength of mixing relative to DCSD. Equation (2) can then be rewritten as:

$$I(D^0 \rightarrow K^+\pi^-)(t) \propto R_{\text{DCSD}}(1 + \sqrt{2\alpha} t \cos\phi + 1/2 \alpha t^2) e^{-t} \quad (3)$$

From this equation, one may read off the following properties: (1) The mixing term peaks at  $t = 2$ . (2) The interference term peaks at  $t = 1$ . (3) A small mixing signature can be greatly enhanced by DCSD through interference (with  $\cos\phi \neq 0$ ) at lower decay times. The ratio between the interference term and the mixing term, denoted  $\xi(t)$ , is given by  $\xi(t) = \sqrt{8/\alpha} \cos\phi/t \propto \sqrt{1/\alpha}$ . So when  $\alpha \rightarrow 0$ ,  $\xi \rightarrow \infty$ . For example, with  $\cos\phi=1$ , at  $t = 1$  for  $\alpha = 10\%, 1\%, 0.1\%, 0.01\%, 0.001\%$  (corresponding to  $R_{\text{mixing}} = 10^{-3}, 10^{-4}, 10^{-5}, 10^{-6}, 10^{-7}$ ) one has  $\xi(t) = 9, 28, 90, 280, 900$  respectively. (4) Only for  $t > \sqrt{8/\alpha} |\cos\phi|$  does the interference term become smaller than the mixing term. (5)  $I(t_0) = 0$  happens and only happens when  $\cos\phi = -1$ , and only at location  $t_0 = \sqrt{2/\alpha}$ . For  $\alpha = 10\%, 1\%, 0.1\%$ , one has  $t_0 = 4.5, 14.1, 44.7$ . (6) One can obtain a very pure DCSD sample by cutting at low decay time:  $t < \zeta \sim 0.1$ . At such low  $t$ , the mixing term drops out and leaving only the interference term. Let's define the purity of DCSD to be  $\mathcal{P}_{\text{DCSD}} = 1 - \int_0^\zeta \sqrt{2\alpha} \cos\phi (te^{-t}) / \int_0^\zeta e^{-t}$ . For  $\zeta \sim 0.1$  one get  $\mathcal{P}_{\text{DCSD}} = \sqrt{2\alpha} \cos\phi \zeta / (2 + \zeta)$ . Let's take  $\zeta = 0.2$ , for  $\alpha = 10\%, 1\%$ , we can get  $\mathcal{P}_{\text{DCSD}} = 96\%, 99\%$  pure DCSD respectively. (7) The cut  $t \leq \zeta$  cuts off only  $1 - (1 + \zeta)e^{-\zeta} \sim \zeta^2/2 = 2\%$  from the whole interference term.

While Property (1) tells us that the mixing term does live at longer decay time, Property (3) tells us clearly that we should not ignore the interference term. In fact, that's the last thing one wants to ignore! (unless we know for sure  $\cos\phi = 0$ ). It is the commonly believed "annoying background", namely DCSD, that could greatly enhance the chance of seeing a very small mixing signal. In semi-leptonic method, one does not have this advantage. For a very small mixing rate, almost all the mixing signature could show up in the interference term, not in the mixing term, as long as  $\cos\phi \neq 0$ . Property (2) tells us at which location one expect to find the richest signature of a potential small mixing, which is where the interference term peaks:  $t \sim 1$  (why should one keep worrying about long lived DCSD tails? let's hope for  $\cos\phi \neq 0$  first.) Property (5) shows that destructive interference is not necessarily a bad thing. In fact, it could provide extra information. For example, if  $\cos\phi = -1$ , then one should find  $I(t_0) = 0$  at  $t_0 = \sqrt{2/\alpha}$ , see Figure 5. For the general case, interference will lead to very characteristic time distribution, as can be clearly seen in Figure 6. Properties (6) and (7) show that we can study DCSD well without being confused by the possible mixing component. This will become important when we discuss method B.

Therefore the signature of mixing is a deviation from a perfect exponential time distribution with the slope of  $\gamma_+^{-1}$ . Our ability to observe this signature depends on the number of  $D^0 \rightarrow K^+\pi^-$  events we will

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<sup>1</sup>One can use  $D^0 \rightarrow K^-\pi^+$  to study the acceptance function versus decay time.

have. Right now this is limited by the rather poor statistics. Figures 3 and 4 show each term with  $\alpha = 10\%$  and  $\cos\phi = \pm 1$  (with  $R_{\text{DCSD}} = 1$ ).

It is interesting to point out here that there is also a possibility, previously unrecognized, of using the Singly Cabibbo Suppressed Decays (SCSD), such as  $D^0 \rightarrow K^+K^-, \pi^+\pi^-$  to study mixing. This is because (assuming CP conservation) those decays occur only through the CP even eigenstate, which means the decay time distribution is a perfect exponential with the slope of  $\gamma_1$ . Therefore, one can use those modes to measure  $\gamma_1$ . The mixing signature is not a deviation from a perfect exponential (again assuming CP conservation), but rather a deviation of the slope from  $(\gamma_1 + \gamma_2)/2$ . Since  $\gamma_+ = (\gamma_1 + \gamma_2)/2$  can be measured by using the  $D^0 \rightarrow K^-\pi^+$  decay time distribution, one can then derive  $y = \gamma_-/\gamma_+ = (\gamma_1 - \gamma_2)/(\gamma_1 + \gamma_2)$ . Observation of a non-zero  $y$  would demonstrate mixing caused by the decay rate difference ( $R_{\text{mixing}} = (x^2 + y^2)/2$ ). It is worth pointing out that in this case other CP even (odd) final states such as  $D^0 \rightarrow K^+K^-K^+K^-$  ( $K^+K^-\pi^0$ ) can be also used to measure  $\gamma_1(\gamma_2)$ . In addition, there is no need to tag the  $D^0$  nor know the primary vertex location, since we only need to determine the slope. I should point out also that this method is only sensitive to mixing caused by the decay rate difference between the two eigen states, not to mixing caused by the mass difference  $x = \delta m/\gamma_+$  ( $\delta m = m_2 - m_1$ ). The sensitivity of this method is discussed in section 4.1.

### 2.1.2 Method B – use difference in resonance substructure

The idea of this new method is to use the wrong sign decay  $D^{*+} \rightarrow D^0\pi_s^+$  followed by  $D^0 \rightarrow K^+\pi^-\pi^0$ ,  $K^+\pi^-\pi^+\pi^-$ , etc., and use the possible differences of the resonant substructure between mixing and DCSD to study mixing. There are good reasons to believe that the resonant substructure of DCSD decay is different from that of mixing (Cabibbo favored decay, CFD). We can use the  $D^0 \rightarrow K^+\pi^-\pi^0$  decay as an example. For CFD and DCSD, the true yield density  $n(p)$  at a point  $p$  in the Dalitz plot can be written as:

$$n(p) \propto |f_1 e^{i\phi_1} A_{3b} + f_2 e^{i\phi_2} BW_{\rho^+}(p) + f_3 e^{i\phi_3} BW_{K^{*-}}(p) + f_4 e^{i\phi_4} BW_{\bar{K}^{*0}}(p)|^2 \quad (4)$$

where  $f_i$  are the relative amplitudes for each component and  $\phi_i$  are the interference phases between each submode.  $A_{3b}$  is the S-wave three-body decay amplitude, which is flat across the Dalitz plot. The various  $BW(p)$  terms are Breit-Wigner amplitudes for the  $K^*\pi$  and  $K\rho$  sub-reactions. Note that in general <sup>2</sup>,

$$f_i^{\text{DCSD}}/f_i^{\text{CFD}} \neq f_j^{\text{DCSD}}/f_j^{\text{CFD}} \quad (i \neq j) \quad (5)$$

$$\phi_i^{\text{DCSD}} \neq \phi_i^{\text{CFD}} \quad (6)$$

This means that the resonant substructure (the true yield density  $n(p)$ ) for DCSD is different from that of mixing <sup>3</sup>. As both DCSD and mixing contribute to the wrong sign decay, the yield density for the wrong sign events  $n_w(p)$  will have a complicated form, due to the fact that for each submode DCSD and mixing may interfere with each other. Just like in method A, for very small mixing, the interference term between DCSD and mixing could be the most important one.

In principle, one can use the difference between the resonant substructure for DCSD and mixing events to distinguish mixing from DCSD. For instance, combined with method A, one can perform a multi-dimensional fit to the data by using the information on  $\Delta M$ ,  $M(D^0)$ , proper decay time  $t$  and the yield density on Dalitz

<sup>2</sup> It has been pointed out [24, 34] that it is unlikely that just one universal suppression factor will affect the individual DCSD. For example, SU(3) breaking can introduce a significant enhancement for  $D^0$  DCSD decays  $D^0 \rightarrow K^+\pi^-, K^{*+}\pi^-$ , while SU(6) breaking can introduce a sizeable suppression relative to the naive expectation for  $D^0$  DCSD decay  $D^0 \rightarrow K^+\rho^-$ .

<sup>3</sup>The sign of the interference between each submode changes whenever  $\cos\theta_R$  ( $\theta_R$  is the helicity angle of the resonance) changes sign. This is the same for both the Cabibbo favored decay and the DCSD. This can be easily seen from the Breit-Wigner amplitude which describes the strong resonances and decay angular momentum conservation:  $BW_R \propto \frac{\cos\theta_R}{M_{ij} - M_R - i\Gamma_R/2}$  where  $M_R$  and  $\Gamma_R$  are the mass and width of the  $M_{ij}$  resonance (the  $K^*$  or  $\rho$ ). The difference between Cabibbo favored decay and DCSD comes from the relative amplitude  $f_i$  for each submode and the interference phase term  $e^{i\phi_i}$ .

plot  $n_w(p, t)$ . The extra information on the resonant substructure will, in principle, put a much better constraint on the amount of mixing. Of course, precise knowledge of the resonant substructure for DCSD is needed here and so far we do not know anything about it. Because of this, for current experiments this method is more likely to be a complication rather than a better method when one tries to apply method A to  $D^0 \rightarrow K^+\pi^-\pi^0$  (see section 3.2 and [25]) or  $D^0 \rightarrow K^+\pi^-\pi^+\pi^-$ . In principle, however, one can use wrong sign samples at low decay time (which is almost pure DCSD, see section 2.1.1.) to study the resonant substructure of the DCSD decays. In the near future, we should have a good understanding of DCSD decays and this method could become a feasible way to search for mixing.

### 2.1.3 Method C —use quantum statistics of the production and decay processes

This method is to search for dual identical two-body hadronic decays in  $e^+e^- \rightarrow \Psi'' \rightarrow D^0\bar{D}^0$ , such as  $(K^-\pi^+)(K^-\pi^+)$ , as was first suggested by Yamamoto in his Ph.D thesis [26]. The idea is that when  $D^0\bar{D}^0$  pairs are generated in a state of odd orbital angular momentum (such as  $\Psi''$ ), the DCSD contribution to identical two-body pseudo-scalar-vector ( $D \rightarrow PV$ ) and pseudo-scalar-pseudo-scalar ( $D \rightarrow PP$ ) hadronic decays (such as  $(K^-\pi^+)(K^-\pi^+)$ ) cancels out, leaving only the contribution of mixing [26, 24, 27]. As many people have asked about this, I would like to show here the essence of Yamamoto's original calculation for the  $(K^-\pi^+)(K^-\pi^+)$  case. Let's define  $e_i(t) = e^{-im_it - \gamma_it/2}$  ( $i = 1, 2$ ) and  $e_{\pm}(t) = (e_1(t) \pm e_2(t))/2$ . A state that is purely  $|D^0\rangle$  or  $|\bar{D}^0\rangle$  at time  $t = 0$  will evolve to  $|D(t)\rangle$  or  $|\bar{D}(t)\rangle$  at time  $t$ , with  $|D(t)\rangle = e_+(t)|D^0\rangle + e_-(t)|\bar{D}^0\rangle$  and  $|\bar{D}(t)\rangle = e_-(t)|D^0\rangle + e_+(t)|\bar{D}^0\rangle$ . In  $e^+e^- \rightarrow \Psi'' \rightarrow D^0\bar{D}^0$ , the  $D^0\bar{D}^0$  pair is generated in the state  $D^0\bar{D}^0 - \bar{D}^0D^0$  as the relative orbital angular momentum of the pair  $\mathcal{L} = 1$ . Therefore, the time evolution of this state is given by  $|D(t)\bar{D}(t')\rangle - |\bar{D}(t)D(t')\rangle$ , where  $t$  ( $t'$ ) is the time of decay of the  $D$  ( $\bar{D}$ ). Now the double-time amplitude  $\mathcal{A}_w(t, t')$  that the left side decays to  $K^-\pi^+$  at  $t$  and the right side decays to  $K^-\pi^+$  at  $t'$ , giving a wrong sign event  $(K^-\pi^+)(K^-\pi^+)$ , is given by:

$$\mathcal{A}_w(t, t') = (e_+(t)e_-(t') - e_-(t)e_+(t'))(a^2 - b^2) \quad (7)$$

where  $a = \langle K^-\pi^+ | D^0 \rangle$  is the amplitude of the Cabibbo favored decay  $D^0 \rightarrow K^-\pi^+$ , while  $b = \langle K^-\pi^+ | \bar{D}^0 \rangle$  is the amplitude of DCSD  $\bar{D}^0 \rightarrow K^-\pi^+$ . Similarly, the double-time amplitude  $\mathcal{A}_r(t, t')$  for the right sign event  $(K^-\pi^+)(K^+\pi^-)$  is given by:

$$\mathcal{A}_r(t, t') = (e_+(t)e_+(t') - e_-(t)e_-(t'))(a^2 - b^2) \quad (8)$$

One measures the wrong sign versus right sign ratio R, which is:

$$R = \frac{N(K^-\pi^+, K^-\pi^+) + N(K^+\pi^-, K^+\pi^-)}{N(K^-\pi^+, K^+\pi^-) + N(K^+\pi^-, K^-\pi^+)} = \frac{\iint \mathcal{A}_w(t, t') dt dt'}{\iint \mathcal{A}_r(t, t') dt dt'} \quad (9)$$

Note in taking the ratio, the amplitude term  $(a^2 - b^2)$  in Equations (7) and (8) drop out. Thus, clearly R does not depend on whether  $b$  is zero (no DCSD) or finite (with DCSD). Integrating over all times, one then obtains  $R = (x^2 + y^2)/2 = R_{\text{mixing}}$ , where  $x$  and  $y$  are defined as before.

This is probably the best way to separate DCSD and mixing. The exclusive nature of the production guarantees both low combinatoric backgrounds and production kinematics essential for background rejection. This method requires one use  $e^+e^-$  annihilation in the charm threshold region. Here the best final state is  $(K^-\pi^+)(K^-\pi^+)$ . In principle, one can also use final states like  $(K^-\rho^+)(K^-\rho^+)$  or  $(K^{*-}\pi^+)(K^{*-}\pi^+)$ , etc., although again there are complications. For example, it is hard to differentiate experimentally  $(K^-\rho^+)(K^-\rho^+)$  from  $(K^-\rho^+)(K^-\pi^+\pi^0)$ , where DCSD can contribute. With high statistics, in principle, this method could be combined with method B.

It has been pointed out that quantum statistics yield different correlations for the  $D^0\bar{D}^0$  decays from  $e^+e^- \rightarrow D^0\bar{D}^0, D^0\bar{D}^0\gamma, D^0\bar{D}^0\pi^0$  [33]. The well-defined coherent quantum states of the  $D^0\bar{D}^0$  can be, in principle, used to provide valuable cross checks on systematic uncertainties and, more importantly, to extract  $x = \delta m/\gamma_+$  and  $y = \gamma_-/\gamma_+$  (which requires running at different energies) if mixing is observed [33].

## 2.2 Semi-leptonic method

The semi-leptonic method is to search for  $D^0 \rightarrow \bar{D}^0 \rightarrow X l^- \nu$  decays, where there is no DCSD involved. However, it usually (not always!) suffers from a large background due to the missing neutrino, in addition, the need to understand the large background often introduces model dependence. In the early days, the small size of fully reconstructed samples of exclusive  $D^0$  hadronic decays and the lack of the decay time information made it difficult to constrain the  $D^0 \bar{D}^0$  mixing rate using the hadronic method, many experiments used semi-leptonic decays. The techniques that were used were similar —searching for like-sign  $\mu^+ \mu^+$  or  $\mu^- \mu^-$  pairs in  $\mu^+ N \rightarrow \mu^+ (\mu^+ \mu^+) X$  [4, 7] and  $\pi^- Fe \rightarrow \mu^+ \mu^+$  [5],  $\pi^- W \rightarrow \mu^+ \mu^+$  [10]. These techniques rely on the assumptions on production mechanisms, and the accuracy of Monte Carlo simulations to determine the large conventional sources of background.

There are other ways of using the semi-leptonic method. The best place to use the semi-leptonic method is probably in  $e^+ e^-$  annihilation near the charm threshold region. The idea is to search for  $e^+ e^- \rightarrow \Psi'' \rightarrow D^0 \bar{D}^0 \rightarrow (K^- l^+ \nu)(K^- l^+ \nu)$  or  $e^+ e^- \rightarrow D^- D^{*+} \rightarrow (K^+ \pi^- \pi^-)(K^+ l^- \nu) \pi_s^+$  [28, 29]. The latter is probably the only place where the semi-leptonic method does not suffer from a large background. It should have a low background, as there is only one neutrino missing in the entire event, threshold kinematics constraints should provide clean signal.

It has been pointed out that one can not claim a  $D^0 \bar{D}^0$  mixing signal based on the semi-leptonic method alone <sup>4</sup> (unless with the information on decay time of  $D^0$ ). Nevertheless, one can always use this method to set upper limit for mixing.

## 3 Mixing Searches at Different Experiments

### 3.1 $e^+ e^-$ running on $\Psi''(3770)$ –MARK III, BES, Tau-charm factory

The MARK III collaboration was the first (though hopefully not the last) to use the  $e^+ e^- \rightarrow \Psi'' \rightarrow D^0 \bar{D}^0$  technique. They reported preliminary results for two “wrong-sign”  $D^0$  decay events (unpublished) [31], one was consistent with  $K^- \rho^+$  vs.  $K^- \rho^+$ , while the other one was consistent with  $K^{*0} \pi^0$  vs.  $K^{*0} \pi^0$ . This was a very interesting result at that time, and had a strong influence on the subject. However, one cannot draw a firm conclusion about the existence of  $D^0 \bar{D}^0$  mixing based on these events. There are at least two reasons: (1) The background study has to rely on Monte Carlo simulation of the PID (particle identification – Time-of-Flight). As Gladding has pointed out: “These results must be considered preliminary because the calculation of the confidence level is sensitive to the tails of PID distribution for the background” [32]; (2) Assuming that the Monte Carlo background study is correct, and that the events are real, one still cannot claim the two events are due to mixing, for example, the non-resonant decays  $D^0 \rightarrow K \pi \pi^0$  may contribute to one side of the pair in each of the events, in which DCSD can contribute.

The MARK III puzzle can be completely solved at a  $\tau$ -charm factory, which is a high luminosity ( $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ )  $e^+ e^-$  storage ring operating at center-of-mass energies in the range 3-5 GeV. The perspectives for a  $D^0 \bar{D}^0$  mixing search at a  $\tau$ -charm factory have been studied in some detail [28, 29]. I will outline here the most important parts. The best way to search for mixing is probably to use  $e^+ e^- \rightarrow \Psi'' \rightarrow D^0 \bar{D}^0 \rightarrow (K^- \pi^+)(K^- \pi^+)$ . The sensitivity is not hard to estimate. Assuming a one year run with a luminosity of  $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ ,  $5.8 \times 10^7$   $D^0$ s would be produced from  $\Psi''$ . Therefore about  $9 \times 10^4$   $(K^- \pi^+)(K^+ \pi^-)$  events would be produced. About 40% of them ( $3.6 \times 10^4$ ) could be fully reconstructed. A detailed study has shown that the potential dominant background comes from doubly misidentified  $(K^- \pi^+)(K^+ \pi^-)$ , and if TOF resolution is 120 ps, this background can be kept to the level of one event or less. This means one can set an upper limit at the  $10^{-4}$  level.

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<sup>4</sup> Bigi [33] has pointed out that an observation of a signal on  $D^0 \rightarrow l^- X$  establishes only that a certain selection rule is violated in processes where the charm quantum number is changed, namely the rule  $\Delta \text{Charm} = -\Delta Q_l$  where  $Q_l$  denotes leptonic charge. This violation can occur either through  $D^0 \bar{D}^0$  mixing (with the unique attribute of the decay time-dependence of mixing), or through new physics beyond the Standard Model (which could be independent of time).

As mentioned section 2.2, the best place to use the semi-leptonic method is probably at a  $\tau$ -charm factory. One good example is to search for  $e^+e^- \rightarrow D^- D^{*+} \rightarrow (K^+\pi^-\pi^+)(K^+l^-\nu)\pi_s^+$ . It is expected that this method can also have a sensitivity at the  $10^{-4}$  level. There are many other independent techniques that one can use for a mixing search at a  $\tau$ -charm factory. By combining several independent techniques (which require running at different energies), it was claimed that  $D^0\bar{D}^0$  mixing at the  $10^{-5}$  level could be observable [29].

There have been several schemes around the world for building a  $\tau$ -charm factory. If such a machine is built, it could be a good place to study mixing. At the workshop, Walter Toki told us the history of the  $\tau$ -charm factory: one was proposed at SLAC in 1989 and at Spain in 1993. It was discussed at Dubna in 1991, at IHEP (China), and at Argonne (this workshop). It will be discussed again at IHEP (China) soon. Let us hope that we will have one in the not too distant future.

### 3.2 $e^+e^-$ running near $\Upsilon(4S)$ –ARGUS, CLEOII, CLEO III, B factory

Using the CLEO II data sample, with an integrated luminosity of  $1.8 \text{ fb}^{-1}$  at and near the  $\Upsilon(4S)$  resonance, CLEO has observed a signal for  $D^0 \rightarrow K^+\pi^-$  [20] from the decay chain  $D^{*+} \rightarrow D^0\pi_s^+ \rightarrow (K^+\pi^-)\pi_s^+$ , as can be seen in Figure 2.

Without a precision vertex detector, CLEO II can only in effect measure the rate  $\mathcal{B}(D^0 \rightarrow K\pi)$  integrated over all times of a pure  $D^0$  decaying to a final state  $K\pi$ . The ratio  $R = \mathcal{B}(D^0 \rightarrow K^+\pi^-) / \mathcal{B}(D^0 \rightarrow K^-\pi^+)$  is given by integrating equation (2) over all times:

$$R = R_{\text{mixing}} + R_{\text{DCSD}} + \sqrt{2R_{\text{mixing}}R_{\text{DCSD}}}\cos\phi \quad (10)$$

CLEO II finds  $R = (0.77 \pm 0.25 \text{ (stat.)} \pm 0.25 \text{ (sys.)})\%$ . This signal could mean one of two things: (1) mixing could be quite large, which would imply that mixing can be observed in the near future; (2) the signal is dominated by DCSD. The theoretical prediction for  $R_{\text{DCSD}}$  is about  $2 \tan^4\theta_C \sim 0.6\%$  [24, 35], which is quite consistent with the measured value. It is, therefore, believed by many that the signal is due to DCSD, although it remains consistent with the current best experimental upper limits on mixing, which are  $(0.37 - 0.7)\%$  [12] and  $0.56\%$  [10].

CLEO has also tried to use hadronic method B, by searching for  $D^0 \rightarrow K^+\pi^-\pi^0$ . The excellent photon detection at CLEO II allows one to study this mode with a sensitivity close to  $D^0 \rightarrow K^+\pi^-$  mode. The main complication faced here is that (as discussed in section 2.1.2) the resonant substructure is not necessarily the same for wrong sign and right sign decays. Because of this, the interpretation of  $R$  as  $R_{\text{mixing}}$  or  $R_{\text{DCSD}}$  will be complicated by the lack of knowledge of the details of the interference between submodes (and also the decay time information). Moreover, one has to worry about the detection efficiency across the Dalitz plot. Setting an upper limit for each submode is clearly very difficult. CLEO has thus set an upper limit on the inclusive rate for  $D^0 \rightarrow K^+\pi^-\pi^0$  as  $R = \mathcal{B}(D^0 \rightarrow K^+\pi^-\pi^0) / \mathcal{B}(D^0 \rightarrow K^-\pi^+\pi^0) < 0.68\%$  [25]. Note this upper limit includes the possible effects of the interference between the DCSD and mixing for each submode as well as the interference between submodes.

This summer, CLEO will install a silicon vertex detector (SVX) with a longitudinal resolution on vertex separation around  $75 \mu\text{m}$ . This will enable CLEO to measure the decay time of the  $D^0$ , and reduce the random slow pion background (as the resolution of the  $D^{*+} - D^0$  mass difference is dominated by the angular resolution on the slow pion, this should be greatly improved by the use of the SVX). By the year 2000, with CLEO III (a symmetric B factory) and asymmetric B factories at SLAC and KEK, each should have about thousands  $D^0 \rightarrow K^+K^-(X), \pi^+\pi^-(X)$  and a few hundred  $D^0 \rightarrow K^+\pi^-$  (and perhaps  $D^0 \rightarrow K^+\pi^-\pi^0, K^+\pi^-\pi^+\pi^-$  too) signal events with decay time information for one year of running. The typical decay length of  $D^0$  ( $\mathcal{L}$ ) is about a few hundred  $\mu\text{m}$ , and the resolution of the decay length ( $\sigma_{\mathcal{L}}$ ) is about  $80 \mu\text{m}$  ( $\mathcal{L}/\sigma_{\mathcal{L}} \sim 3$ ). The sensitivity to mixing at CLEO III and asymmetric B factory has not been carefully studied yet. A reasonable guess is that it could be as low as  $10^{-4}$ . If mixing is indeed as large as DCSD, it should be observed by then.

### 3.3 Fixed target experiments—E615, E691, E791, E687, E831

A significant amount of our knowledge has been gained from Fermilab fixed target experiments, and in fact the current best upper limits on mixing have emerged from these experiments (E615, E691), and will come from their successors E687, E791 and E831 soon.

The best upper limit using the semi-leptonic method comes from the Fermilab experiment E615, which used a 255 GeV pion beam on a tungsten target. The technique is to search for the reaction  $\pi N \rightarrow D^0 \bar{D}^0 \rightarrow (K^- \mu^+ \nu) D^0 \rightarrow (K^- \mu^+ \nu)(K^- \mu^+ \nu)$ , where only the final state muons are detected (like sign  $\mu^+ \mu^+$  or  $\mu^- \mu^-$  pairs). Assuming  $\sigma(c\bar{c}) \sim A^1$  nuclear dependence, they obtained  $R_{\text{mixing}} < 0.56\%$  [10].

The best upper limit using the hadronic method by measuring the decay time information comes from E691, which is the first high statistics fixed target (photoproduction) experiment. In fact, E691 was the first experiment which used the decay time information (obtained from the excellent decay time resolution of their silicon detectors) to distinguish DCSD and mixing. The decay chains  $D^{*+} \rightarrow D^0 \pi_s^+$  followed by  $D^0 \rightarrow K^+ \pi^-$ ,  $K^+ \pi^- \pi^+ \pi^-$  were used. The upper limits from the  $D^0 \rightarrow K^+ \pi^-$  mode are  $R_{\text{mixing}} < (0.5 - 0.9)\%$  and  $R_{DCSD} < (1.5 - 4.9)\%$ , while the upper limits from  $D^0 \rightarrow K^+ \pi^- \pi^+ \pi^-$  are  $R_{\text{mixing}} < (0.4 - 0.7)\%$  and  $R_{DCSD} < (1.8 - 3.3)\%$ . The combined result gives  $R_{\text{mixing}} < (0.37 - 0.7)\%$ . The ranges above reflect the possible effects of interference between DCSD and mixing with an unknown phase( $\phi$ ). Note that for  $D^0 \rightarrow K^+ \pi^- \pi^+ \pi^-$ , the resonant substructure in the Cabibbo favored and DCSD decays has been ignored.

At this workshop, both E687 and E791 have reported their preliminary result from part of their data. One can find the details in Jim Wiss's talk. The best upper limits on mixing should come from these two experiments soon. It is worth pointing out here that both the E687 and E791 results reported in the workshop are based on the assumption that there is no interference between DCSD and mixing. Future analysis should include the interference term for the reasons discussed in section 2.1.1.

## 4 Comparison of Different Experiments

### 4.1 Hadronic method A

This measurement requires: (1) excellent vertexing capabilities, at least good enough to see the interference structure; (2) low background around the primary vertex. The background level around the primary vertex could be an important issue as the interference term in equation (2) does peak at  $t = 1$ . In addition, low background around primary vertex means that one does not suffer much from random slow pion background and also one can measure the DCSD component at low decay time well. This is important for understanding DCSD at large decay times. The vertexing capabilities at  $e^+e^-$  experiments ( $\mathcal{L}/\sigma \sim 3$ ) for CLEO III and asymmetric B factories at SLAC and KEK should be sufficient for a mixing search. The extra path-length due to the Lorentz boost, together with the use of silicon detectors for high resolution position measurements, have given the fixed target experiments an advantage over  $e^+e^-$  experiments ( $\mathcal{L}/\sigma \sim 8 - 10$ ). The low background around the primary vertex at  $e^+e^-$  experiments and photoproduction experiments is a certain advantage. It is worth pointing out here that at the  $e^+e^-$  experiments (esp. at asymmetric B factory or Z factory) it maybe possible to use  $B^0 \rightarrow D^{*+} l^- \nu$ , where the primary ( $D^{*+}$  decay) vertex can be determined by the  $l^-$  together with the slow pion coming from the  $D^{*+}$ . In this case, the background level around the primary vertex is intrinsically very low.

However, in the case of  $D^0 \rightarrow K^+ K^-, \pi^+ \pi^-, \text{etc.}$ , the requirement on the background level around the primary vertex is not so important. In this case, the mixing signature is not a deviation from a perfect exponential (again assuming CP conservation), but rather a deviation of the slope from  $(\gamma_1 + \gamma_2)/2$ . It is worth pointing out that there are many advantages with this method. For example, one can use Cabibbo favored decay modes, such as  $D^0 \rightarrow K^- \pi^+$ , to measure the average  $D^0$  decay rate  $(\gamma_1 + \gamma_2)/2$ . This, along with other SCSD CP even (or odd) final states, would allow for valuable cross checks on systematics uncertainties. In addition, since we only need to determine the slope here, we do not need to tag the  $D^0$  nor know the primary vertex location. The sensitivity of this method depends on how well we can determine the slope. Roughly speaking, in the ideal case, the sensitivity to  $y$  would be  $\sim 1/\sqrt{N}$ , where  $N$  is the number



of  $D^0 \rightarrow K^+K^-, \pi^+\pi^-$ , etc. events, which means that the sensitivity to mixing caused by the decay rate difference ( $\sim y^2/2$ ) would be close to  $\sim 1/N$ . For example, a fixed-target experiment capable of producing  $\sim 10^8$  reconstructed charm events could lower the sensitivity <sup>5</sup> to  $\sim 10^{-5} - 10^{-6}$  level for the  $y^2$  term in  $R_{\text{mixing}} = (x^2 + y^2)/2$ .

## 4.2 Hadronic method B

In the near future, we should be able to have a good understanding of DCSD <sup>6</sup> in  $D^0 \rightarrow K^+\pi^-\pi^0$ ,  $D^0 \rightarrow K^+\pi^-\pi^+\pi^-$ , etc. modes, then method B will become a feasible way to study mixing and the sensitivity should be improved. Just like method A, this method requires very good vertexing capabilities and very low background around the primary vertex (this is even more important than in method A, since precise knowledge of DCSD is very important here). In addition, this method requires that the detection efficiency (for the mode being searched) across Dalitz plot be quite uniform (at least the detector should have good acceptance on the Dalitz plot at locations where DCSD and mixing resonant substructure are different). This is necessary so that detailed information on the resonant substructure can be obtained in every corner on the Dalitz plot.

The excellent photon detection capabilities will allow  $e^+e^-$  experiments to study the  $D^0 \rightarrow K^+\pi^-\pi^0$  mode with very low background. From the CLEO II  $D^0 \rightarrow K^+\pi^-\pi^0$  analysis, the detection efficiency across the Dalitz plot will have some variations due to cuts needed to reduce background, however, it is still good enough to obtain detailed information on the resonant substructure [25]. Future fixed target experiments may have a good chance to study  $D^0 \rightarrow K^+\pi^-\pi^+\pi^-$  mode, since the detection efficiency across Dalitz plot should be quite flat. The sensitivity that each experiment can reach by using this method depends on many things and need to be carefully studied in the future.

## 4.3 Hadronic method C

The sensitivity of this method depends crucially on the particle identification capabilities. Since the  $D^0$  is at rest, the  $K$  and  $\pi$  mesons will have the same momentum, so a doubly misidentified Cabibbo favored decay  $D^0 \rightarrow K^-\pi^+$  ( $K^- \rightarrow \pi^-, \pi^+ \rightarrow K^+$ ) mimics a  $D^0 \rightarrow K^+\pi^-$  with almost the same  $D^0$  mass. It is worth pointing out here that particle identification is not as crucial to method A as it is to this method (C), as far as this particular background is concerned. This is because in method A, the  $D^0$  is highly boosted, and doubly misidentified  $D^0 \rightarrow K^+\pi^-$  decays will have a broad distribution in the  $D^0$  mass spectrum around the  $D^0$  mass peak; this background can be kinematically rejected with only a small reduction of the efficiency for the signal events <sup>7</sup>.

Once the sensitivity reaches  $\mathcal{O}(10^{-5})$ , one may have to worry about other contributions, such as contributions from continuum background, contributions from  $e^+e^- \rightarrow 2\gamma \rightarrow D^0\bar{D}^0$  which may produce C-even states where DCSD can contribute [27].

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<sup>5</sup>Since I came up with this idea the day before the deadline of this paper, the sensitivity has not been carefully estimated yet.

<sup>6</sup>It may be possible that good understanding of DCSD can be reached by measuring the pattern of  $D^+$  DCSD decays where the signature is not confused by a mixing component. It is worth pointing out that the  $D^+$  DCSD decays can be studied very well at future fixed target experiments.

<sup>7</sup>The idea is for each  $K^+\pi^-$  candidates, one can invert the kaon and pion assignments and recalculate the  $D^0$  mass, denoted  $M_{\text{flip}}$ . If  $M_{\text{flip}}$  lies close to the nominal  $D^0$  mass, the combination is discarded. This veto works as long as the momentum measurement is correct. One can say that excellent tracking capabilities is crucial in order to get rid of this background here.

#### 4.4 Semi-leptonic method

The semi-leptonic method usually suffers from large background (except at a  $\tau$  charm factory), the traditional method of looking for like sign  $\mu^+\mu^+$  or  $\mu^-\mu^-$  pairs is an example. New ideas are needed in order to improve the sensitivity significantly. Some promising techniques have been suggested by Rolly Morrison and others, and have been discussed in the working group [30].

### 5 Summary

The search for  $D^0\bar{D}^0$  mixing carries a large discovery potential for new physics since the  $D^0\bar{D}^0$  mixing rate is expected to be very small in the Standard Model. The past decade has seen significant experimental progress in sensitivity (from 20% down to 0.37%).

In light of the recent CLEO II signal in  $D^0 \rightarrow K^+\pi^-$ , if the mixing rate is close to that of DCSD (above  $10^{-4}$ ), then it might be observed by the year 2000 with either the hadronic or the semi-leptonic method, either at fixed target experiments, CLEO III, asymmetric B factories (at SLAC and KEK), or at a  $\tau$ -charm factory. If the mixing rate is indeed much smaller than DCSD, then the hadronic method may have a better chance as the potentially very small mixing signature could be enhanced by the presence of the relatively large “annoying background” DCSD. The design of future experiments should focus on improving the vertexing capabilities and reducing the background level around the primary vertex, in order to fully take advantage of having the possible DCSD interference. In addition, the very complication due to the possible differences between the resonant substructure in many DCSD and mixing decay modes  $D^0 \rightarrow K^+\pi^-(X)$  could in principle be turned to advantage by providing additional information once the substructure in DCSD is understood (method B) and the sensitivity could be improved significantly this way. This means that understanding DCSD in  $D$  decays could be a very important step on the way to observe mixing. Experimenters and theorists should work hard on this.

In the case of  $D^0 \rightarrow K^+\pi^-(X)$  and  $D^0 \rightarrow X^+l^-$ , we are only measuring  $R_{\text{mixing}} = (x^2 + y^2)/2$ . Since many extensions of the Standard Model predict large  $x = \delta m/\gamma_+$ , it is very important to measure  $x$  and  $y$  separately. Fortunately, SCSD can provide us information on  $y$ . This is due to the fact that decays such as  $D^0 \rightarrow K^+K^-, \pi^+\pi^-$ , occur only through definite CP eigenstate, and this fact can be used to measure the decay rate difference  $y = \gamma_-/\gamma_+ = (\gamma_1 - \gamma_2)/(\gamma_1 + \gamma_2)$  alone. Observation of a non-zero  $y$  would demonstrate mixing caused by the decay rate difference. This, together with the information on  $R_{\text{mixing}}$  obtained from other methods, we can in effect measure  $x$ . In this sense, it is best to think of the quest to observe mixing (new physics) as a program rather than a single effort.

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Figure 1: The quest for  $D^0\bar{D}^0$  mixing. Note that the range in E691 result reflects the possible effects of interference between DCSD and mixing, and the CLEO II signal could be due to either mixing or DCSD, or a combination of the two.

Figure 2: The CLEO II signal for  $D^0 \rightarrow K^+\pi^-$ . The  $D^0$  mass for wrong sign events. (a) for events in the  $\Delta M$  peak; (b) for events in the  $\Delta M$  sidebands. The solid lines are the fits using the corresponding right sign mean and  $\sigma$  in data.

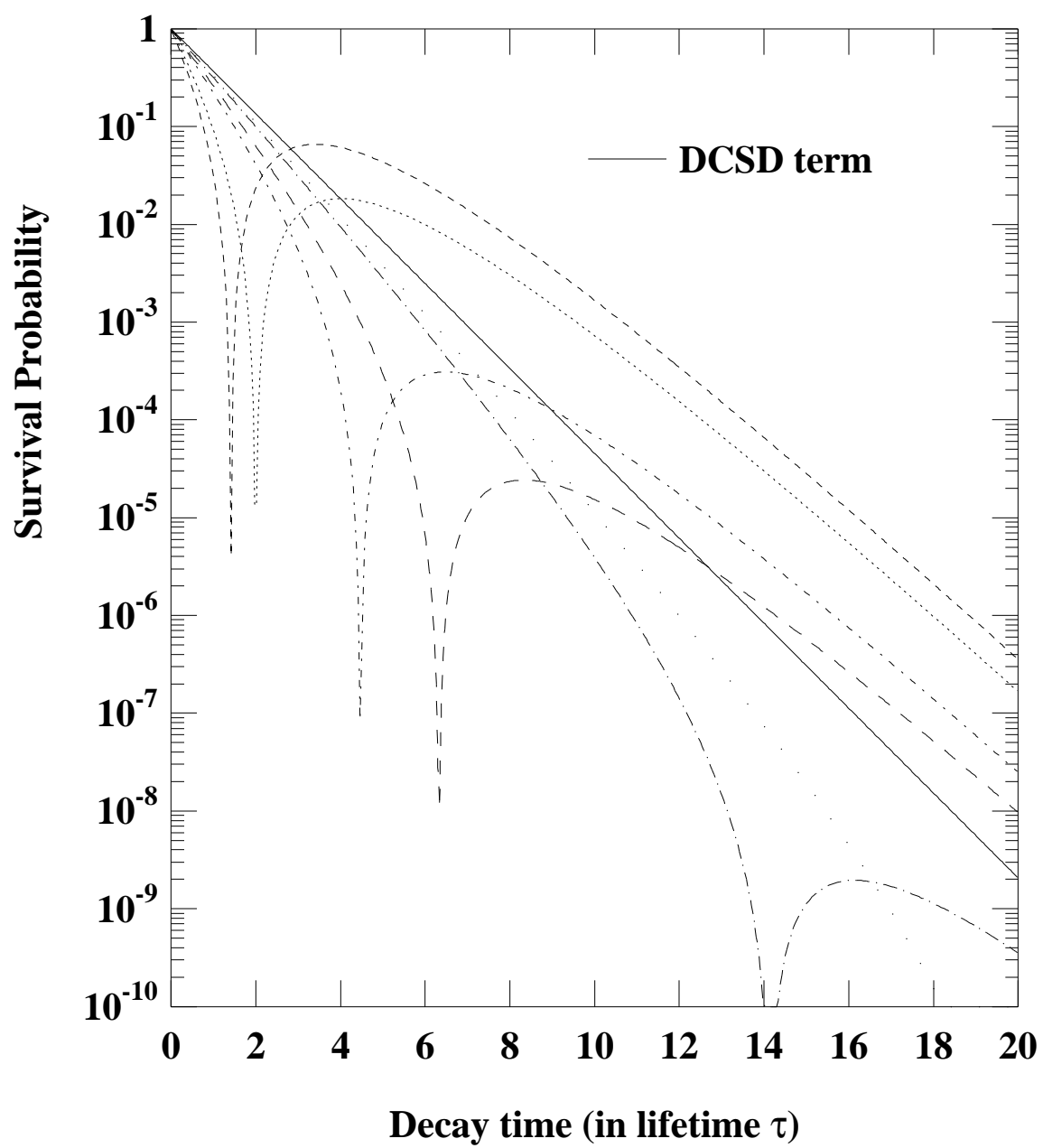
Figure 3: The decay time dependence of DCSD and mixing with  $\alpha = R_{\text{mixing}}/R_{\text{DCSD}} = 10\%$ .

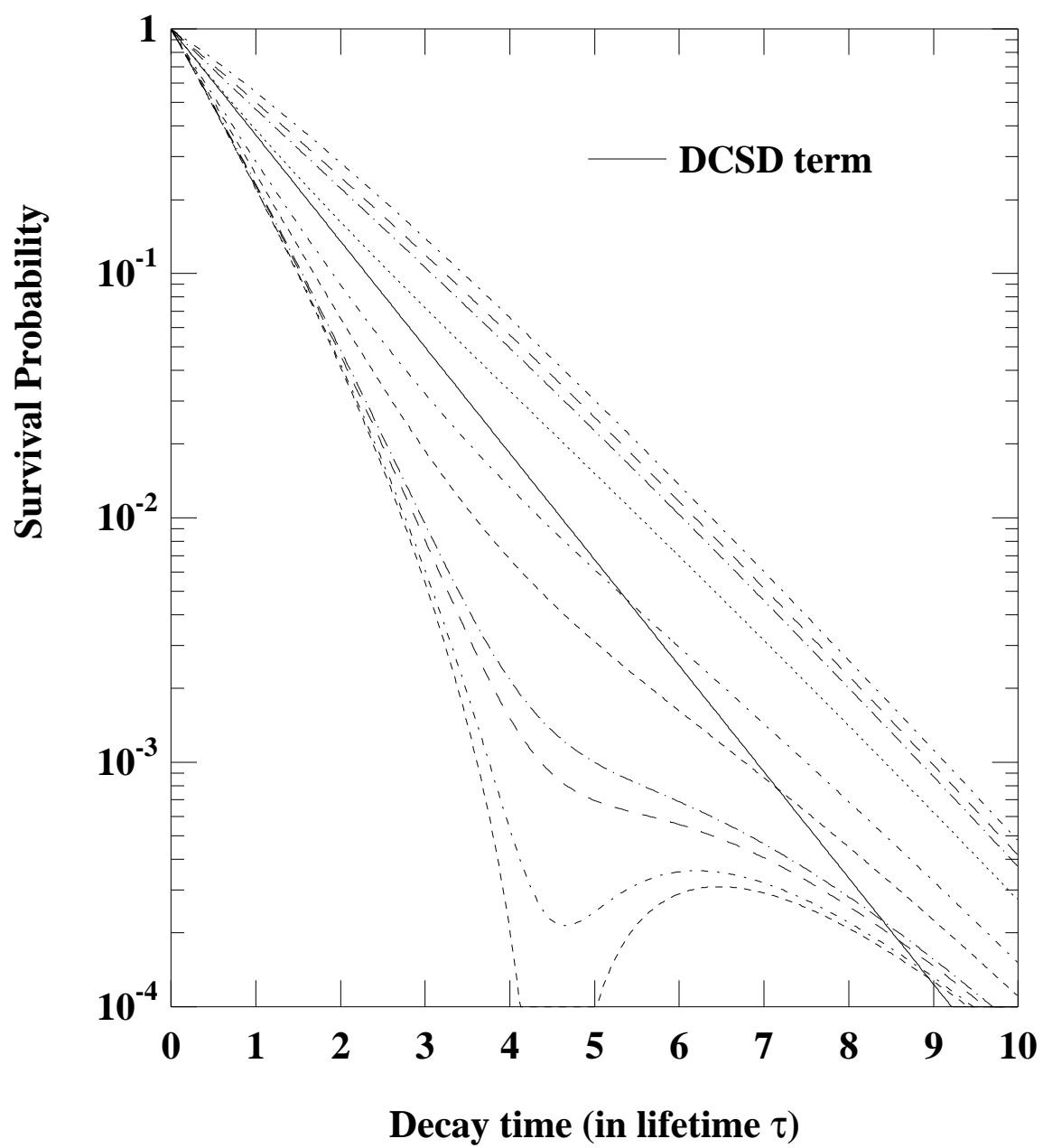
Figure 4: The decay time dependence of DCSD and mixing with  $\alpha = R_{\text{mixing}}/R_{\text{DCSD}} = 10\%$ , in log scale.

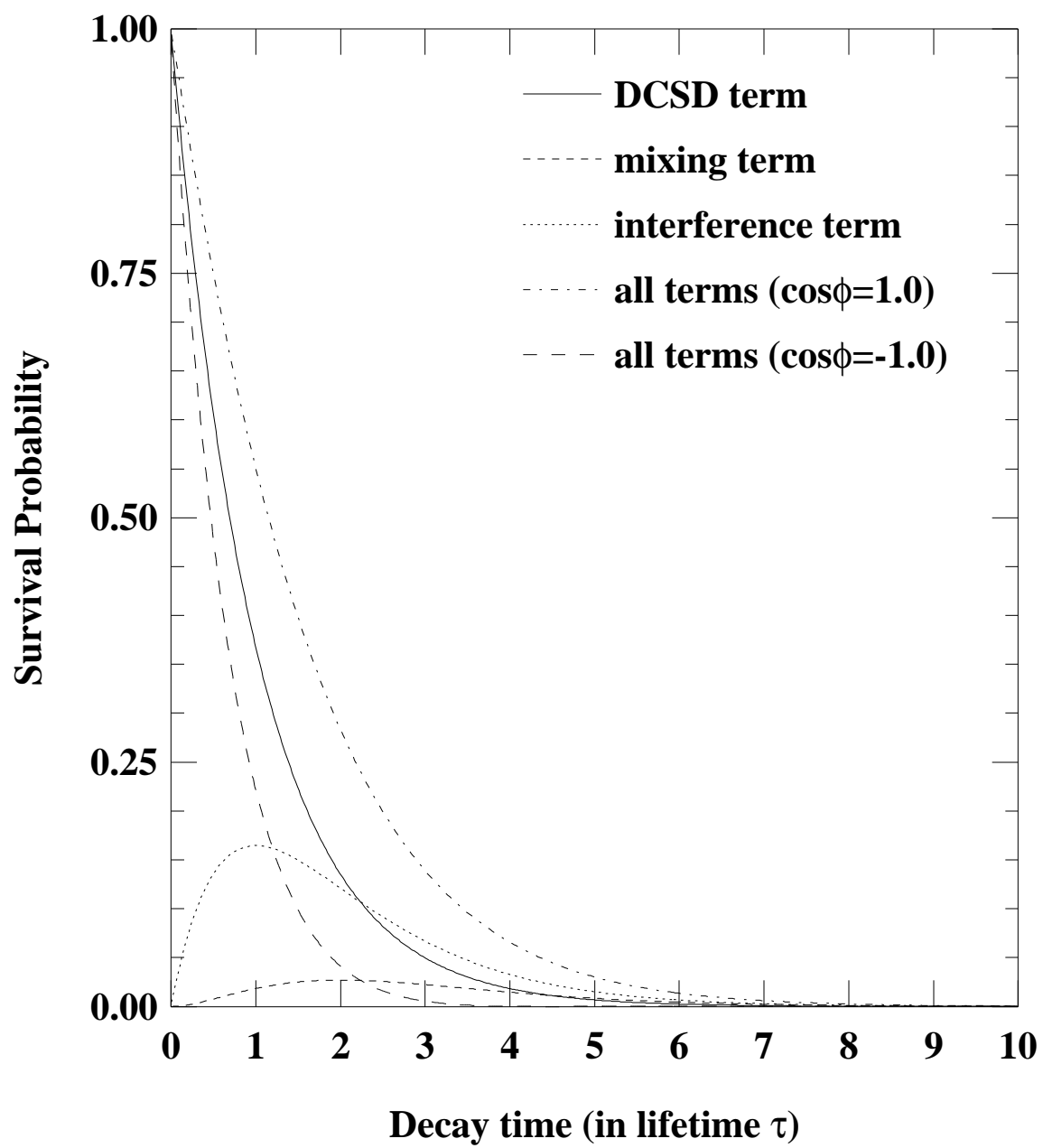


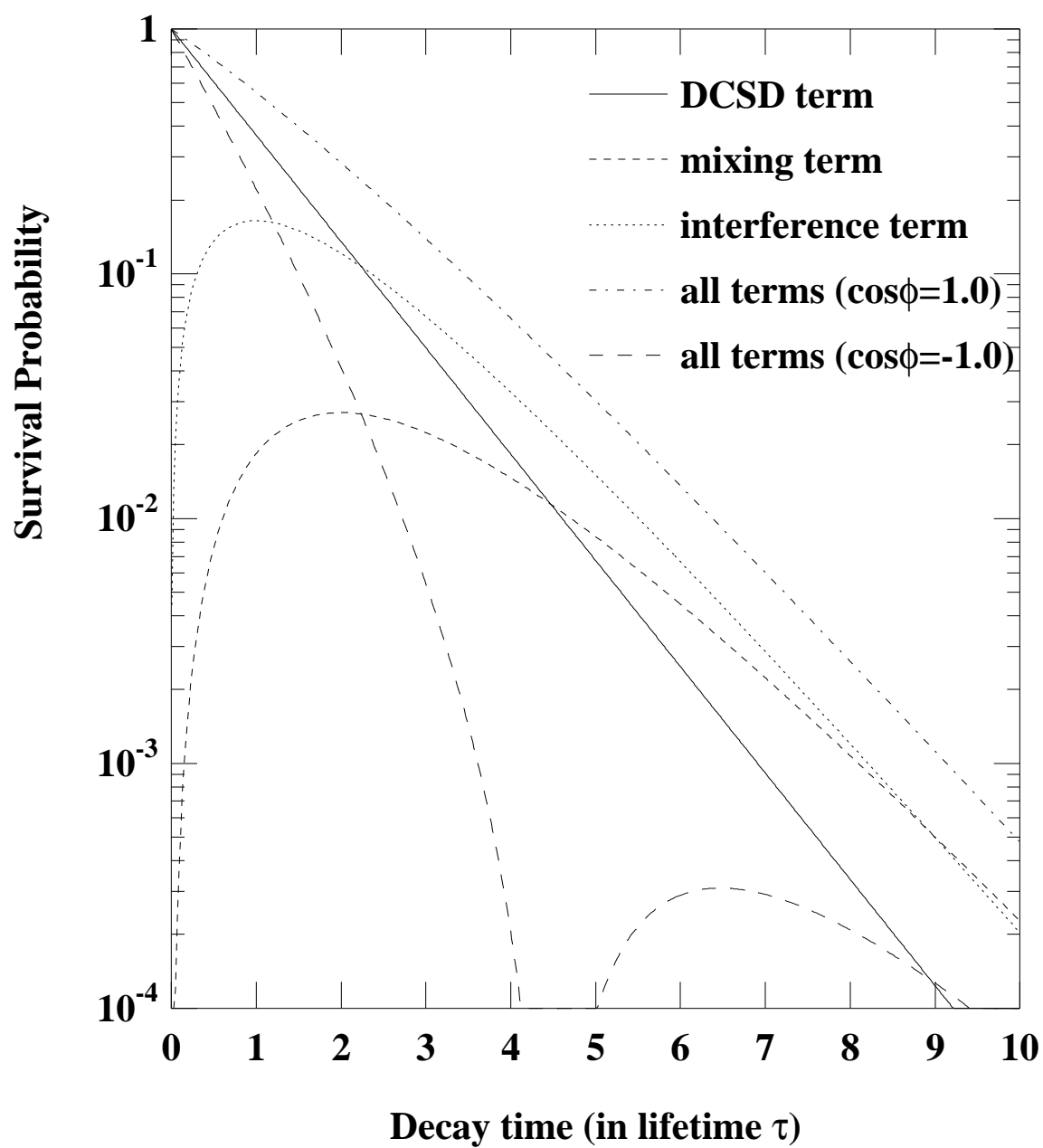
Figure 5: The decay time dependence of DCSD and mixing with maximal destructive interference  $\cos\phi = -1.0$ . For different  $\alpha = R_{\text{mixing}}/R_{\text{DCSD}}$  values: from left to right,  $\alpha = 100\%, 50\%, 10\%, 5\%, 1\%, 0.5\%$  (with  $R_{\text{DCSD}} = 10^{-2}$ , this corresponds to  $R_{\text{mixing}} = 10^{-2}, 5 \times 10^{-3}, 10^{-3}, 5 \times 10^{-4}, 10^{-5}, 5 \times 10^{-6}$ ).

Figure 6: The decay time dependence of DCSD and mixing with  $\alpha = R_{\text{mixing}}/R_{\text{DCSD}} = 10\%$ . For different  $\cos\phi$  values: from bottom to top,  $\cos\phi = -1.0, -0.99, -0.96, -0.94, -0.80, -0.6, 0.0, 0.5, 0.7, 1.0$ . The solid line is the DCSD term, as a reference line.









# The Quest for Charm Mixing

